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# Neutron Transfer to the Continuum Reactions*

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## Abstract

In this contribution we show that the theory of neutron transfer to the continuum reactions is an useful tool to study different characteristics of the single particle structure of nuclei. In one example we discuss properties of the single particle resonances in $^{208}Pb$. Another interesting application deals with the neutron breakup from weakly bound nuclei. Here one can use the theoretical calculations to help establishing the angular momentum of the decaying state which is experimentally not known.

## I. INTRODUCTION

Transfer to the continuum reactions are quasi-elastic, peripheral heavy-ion reactions in which the projectile of mass number $A_P$, transfers a nucleon to a target continuum final state of positive energy. The ejectile nucleus of mass number $(A_P - 1)$ is scattered at very forward angles with almost the beam energy. This kind of reactions are relevant in the medium-high beam energy domain where the incident energy per nucleon exceeds the nucleon average binding energy. The mean energy loss is close to the incident energy per nucleon. Ejectile angular distributions are featureless while the inclusive ejectile energy loss spectra show interesting features and by energy conservation are converted into residual nucleus excitation energy spectra. Projectile excitations are restricted to those leaving the ejectile in an excited state below particle emission threshold since it is the $(A_P - 1)$ nucleus which is detected.

The theory gives the following form of the neutron final energy ($\varepsilon_f$) spectrum [1]

$$\frac{dP}{d\varepsilon_f} \approx \Sigma_{l_f}(|1 - \langle S_{l_f}\rangle|^2 + 1 - |\langle S_{l_f}\rangle|^2)B(l_f, l_i). \tag{1.1}$$

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Eq.(1.1) can be easily transformed [2] into a neutron momentum distribution which is related to the measured ejectile momentum distribution. The physical interpretation is that the projectile brings up the neutron which is scattered into a continuum state by the target. The neutron-target interaction, in each partial wave $l_f$, is represented by the optical model S-matrix for scattering of a free neutron by the target nucleus. The first term of Eq.(1.1), proportional to $|1-\langle S_{l_f}\rangle|^2$, gives the neutron elastic breakup spectrum in which the target is left into its ground state while the second term proportional to the transmission coefficient $T = 1 - |\langle S_{l_f}\rangle|^2$ gives the absorption spectrum [1]. This term contains contributions from inelastic scattering of the breakup neutron by the target nucleus and also from compound nucleus formation. The factor $B(l_f, l_i)$ is an elementary transfer probability which depends on the details of the initial and final states, on the energy of relative motion and on the distance of closest approach $d$ between the two nuclei. In particular B contains as one of its factors the initial neutron parallel momentum distribution in the projectile. The other factors depend smoothly on the final neutron energy in the case of a very weakly bound initial state of low angular momentum (s or p). In other cases the dependence can be quite important and it introduces strong distortion effects on the initial momentum distribution.

We obtain the final cross section, in the strong absorption hypothesis for the relative motion which is treated classically, by an integration of Eq.(1.1) over all distances of closest approach $d$ larger than the strong absorption radius [1,2].

This paper is concerned with two applications of the theory of transfer to the continuum reactions to the study of

- Damping of single particle resonance states in the continuum.
- Structure of weakly bound nuclei.

## II. APPLICATIONS

The first example we wish to discuss is the reaction $^{208}Pb(^{40}Ar,^{39}Ar)^{209}Pb$ at $E_{inc} = 41MeV/u$ whose inclusive energy spectrum [3] is given in Fig.(1). The full curve is the cross section calculated using Eq.(1.1). The close dotted curve is the elastic breakup obtained taking into account only the first term of Eq.(1.1). Absorption effects dominate in this reaction.

We show also the energy distribution of the individual final angular momentum terms $l_f = 8, 9, 10$ from the absorption part of Eq.(1.1). Solid, dashed and dotdashed curves respectively. These terms give the cross section for transfer to a particular final angular momentum state in the residual nucleus and therefore represent the strength function for the corresponding single particle state. The data shows a bump around 12 MeV excitation energy which is meanly due to the $k_{17/2}$ state, but also another peak around 20 MeV which according to the calculation originates from the $l_f = 10$ state which is still not completely damped. The physical reason for such a behavior is that these states have high angular momentum, their high centrifugal barriers keep them well inside the nuclear potential and there is little mixing with low angular momenta states from which collective behavior and damping usually originate. A detailed discussion about the possibility of finding states with dominant single particle characteristics in such a high excitation energy range, can be found in [4].

This reaction has also another interesting characteristic, namely that there are several possible initial states contributing. Transfer from each of them would still leave the ejectile in a state excited below particle threshold. Due to the finite experimental energy resolution the data contains contributions from all of them. These initial states have different angular momenta and therefore quite different initial momentum distributions. As a consequence the shape of the spectra due to each of them are rather different, as shown in Fig.(2). Solid line, dotted, dashed and close dotted refer respectively to $2s_{1/2}$, $1d_{3/2}$, $2p_{3/2}$, $1f_{7/2}$ initial states. This is a very interesting characteristic of transfer to the continuum reactions. Distortion effects caused by the neutron final state interaction with the target are quite evident in this reaction [3] because of the dominant absorption effect of the neutron on the target.

In the case of weakly bound nuclei breakup dominates. Lately the interest on this class of processes has been renewed by the advent of radioactive beams [5] which are made up of unstable nuclei. These nuclei have one or two nucleons in a state of very weak binding energy. As a consequence the nucleon wave function has an extended tail and one talks of 'halo nuclei' [6]. In this case the reaction is a good probe of the nucleon momentum distribution in the projectile. However spectra due to different initial angular momenta have different widths and sometimes different shapes.

For example the neutron breakup from weakly bound carbon isotopes has recently been measured [7]. These nuclei show interesting mixing of s-d orbits in their last bound state wave functions but the exact amount of each component has not been established yet. Comparison of experimental data to theoretical calculation can help solving this problem. We show in Figs.(3) and (4) the neutron parallel momentum distribution from the breakup of $^{19}C$ and $^{17}C$ respectively on a $^{9}Be$ target. In the first case the calculation from Eq.(1.1) reproduces the data if both s and d initial state contributions are included with a dominant d (90%) occupation probability. The s-contribution is responsible for the narrow width at the top of the distribution but the tails of the distribution are due to the d-component. In the $^{17}C$ case instead the breakup from the d-state dominates completely and the final momentum distribution is double peaked as the initial d distribution shown in Fig.(5). In both Figs.(4) and (5) the dotdashed line is the d-distribution while the solid line is the s-distribution. However comparing the distributions in Figs (4) and (5) we notice that the reaction mechanism has introduced some distortion which can be seen in the data and it is reproduced by the calculation. The origin of the distortion is in the mixing of the initial parallel and transverse momentum distributions, induced by the reaction mechanism. We discuss this effect in a forthcoming publication. It is more evident for initial angular momenta higher than $l = 0, 1$, partially because the experiment as well as the calculation make an average over the the initial angular momentum projections.

Finally we mention that processes initiated by two-neutron halo nuclei are still under debate as it can happen that one neutron breaks up close to the interaction region with the target, while the other decays in flight [8] due to a non negligible final state interaction with the projectile. This has been seen clearly to happen in the case of $^{6}He$ [9].

**Acknowledgment**

This is the twentieth year since I started to collaborate with D. M. Brink. I wish to thank him for his extraordinary example of clearness and rigor in Physics as well as in life.

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**Figure Captions**

Fig. (1). $^{208}Pb(^{40}Ar,^{39}Ar)^{209}Pb$ at $E_{inc} = 41MeV/u$.

Fig. (2). Spectra for different initial states.

Fig. (3). Neutron parallel momentum distribution from $^{19}C$ breakup.

Fig. (4). Neutron parallel momentum distribution from $^{17}C$ breakup.

Fig. (5). Neutron momentum distribution for $l = 0, 2$.

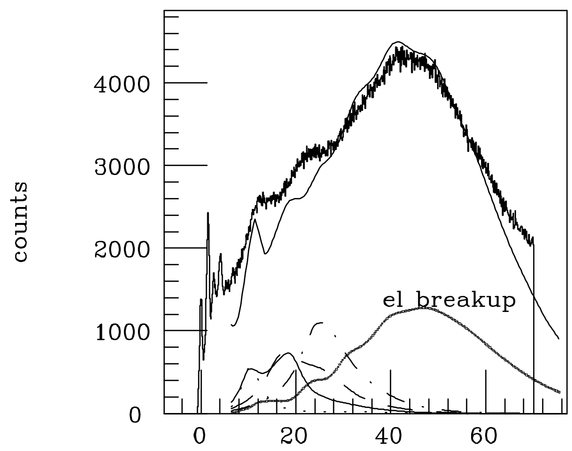

counts
4000
3000
2000
1000
0
0
20
40
60
el breakup
$E_x$ (MeV)

Fig.1

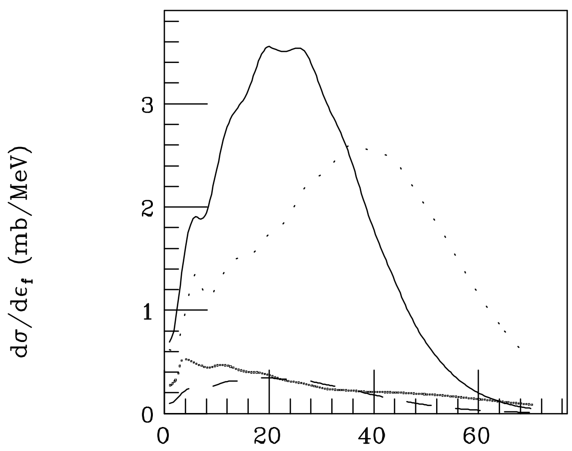
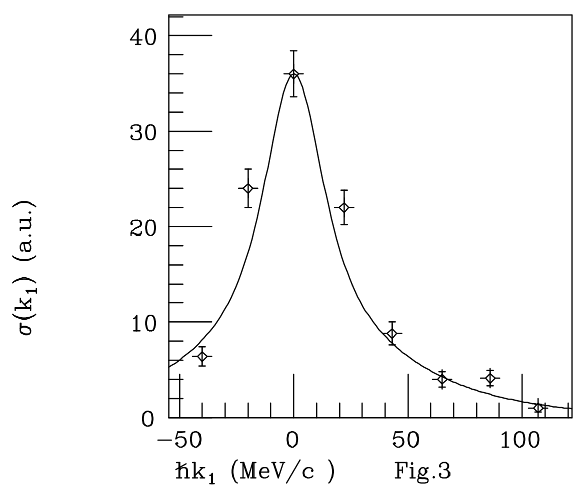
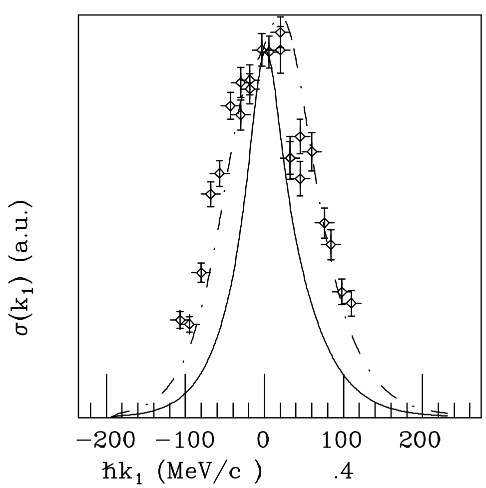

$d\sigma/d\epsilon_f$ (mb/MeV)
3
2
1
0
0
20
40
60
$\epsilon_f$ (MeV)

Fig.2



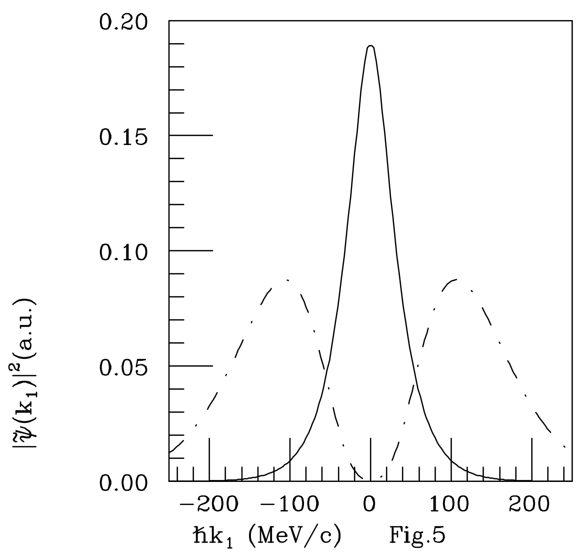
σ(k₁) (a.u.)
40
30
20
10
0
−50
0
50
100
ħk₁ (MeV/c )


Fig.3



σ(k₁) (a.u.)
−200
−100
0
100
200
ħk₁ (MeV/c )


.4



|ψ̃(k₁)|²(a.u.)
0.20
0.15
0.10
0.05
0.00
−200
−100
0
100
200
ħk₁ (MeV/c)


Fig.5